DETECTION OF FIRST AND SECOND CARDIAC SOUNDS BASED ON TIME FREQUENCY ANALYSIS

M. A. R. Santos[1], M. N. Souza[1,2], *Member IEEE*
[1]Biomedical Engineering Program – COPPE, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
[2] Electronic Department E.E., Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

Abstract -**Determining the exact timing of cardiac events, represented by the first (S1) and second (S2) sounds, from the PCG signals (*phonocardiogram*), represents a great challenge, specially in pathological cases. A system that allows this kind of detection could be used to synchronize several important biomedical devices and diagnosis techniques, such as intraaortic balloons (IABP) and synchronous images of Ultrasound, Magnetic Resonance and Computerized Tomography. This work presents a wavelet-based technique for S1 and S2 detection in PCG signals, that is able to perform a good detection in both normal and abnormal cases. It will be shown the criterion of choosing the most suitable wavelet from a set of classical ones, as well as the principles of the final detection method. The results in the analysis of 756 cardiac cycles, from 19 subjects, including normal and abnormal ones present an error ratio of 0.8%, point out to the efficiency of the proposed method.**

Keywords **- Wavelet Transform, Cardiac Sounds, Phonocardiogram, Eletrocardiogram.**

I. INTRODUCTION

The study of Phonocardiogram (PCG) and Eletrocardiogram (ECG) signals, supply relevant information about the heart functioning. The literature has shown that many authors aimed to determine the exact timing of cardiac events from PCG signals [2][6]. Such methods could be used, e.g., in the synchronism of IABP, replacing the normally used ECG signals, considering that PCG signals are directly related to the mechanical events of the heart and ECG is related to the electrical activity of the heart. Despite the amount of published papers concerning with the detection of PCG timing, most of them only present good results in normal cases, showing great timing errors in cases where the real necessity of IABP would be indicated, i.e., in pathological subjects.

This work deals with developing an objective technique that allows the correct identification of S1 and S2 in the PCG signals, even in pathological cases, where systolic and diastolic murmurs difficult the detection of such events. The proposed technique is based on the Wavelet Transform (WT) time-frequency analysis, due to its good performance in analyzing non-stationary signals, the type of signal derived from the closing/opening of heart valves [3][4][6].

It will be shown that the proposed method results in a very precise timing of PCG signals and, as mentioned before, the final technique presents relevancy not only in synchronizing IABP, but also in synchronized imaging techniques.

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II. METHODOLOGY

In this section a brief review of the cardiac sounds genesis and WT will be described, as well as the adopted criterion to choose the best mother wavelet from a set of classical wavelet families and the description of the proposed technique.

A. Cardiac Sounds

The most important cardiac sounds, S1 and S2, are generated by sudden distention of the valves leaflets or by acceleration of blood mass in the moment of ventricular contraction. Their irradiation through the thorax surface is governed by the site of its origin and by the original intensity of the signal.

Normal sounds that are generated by the left heart are generally strong and can be detected in all the *precordium.* Sounds originated in the right heart are strictly limited to the left external border, between second and third intercostal spaces[5]. Considering these facts, it is clear that PCG are non-stationary signals and that they must be analyzed by a time-frequency method, that in the present case is the WT [3].

B. Wavelet Transform

The WT has been used in many knowledge fields, ranging from Communications to Biology [4]. Due to its good performance in the analysis of signals that present non-stationary characteristics, they have become a powerful alternative when compared to the traditional Fourier Transform (FT).

The classical FT decomposes a signal, in time domain, using a base of orthogonal sinusoidal functions. The WT, by the other hand, presents a decomposition base whose constituents are obtained through expansions, contractions and shifts of a same basic function, called mother wavelet, that can be selected according to the analyzed signal [3]. For the dyadic case, the mother wavelet must satisfy (1), that correlates it with the so-called scaling function, that must satisfy (2)

$$y(t) = \sqrt{2} \sum_{n=0}^{k} h_1(k) f(2t-k) \quad (1)$$

$$f(t) = \sqrt{2} \sum_{n=0}^{k} h_0(k) f(2t-k) \quad (2)$$

where $j, k \in Z$, h_0 and h_1 are coefficients associated with the impulsive response of a low-pass and high-pass FIR (Finite

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Abstract

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Impulse Response) filters, respectively. Thus, the WT can also be performed by a filter-bank tree approach, as illustrated in Fig. 1[3].

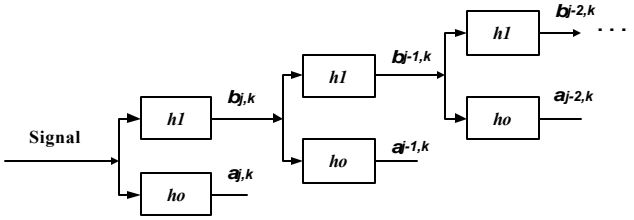

Fig. 1. Block diagram of the filter-bank tree. The h_0 and h_1 are the impulsive response of the FIR filters and $a_{j,k}$ and $b_{j,k}$ the approximation and detail coefficients, respectively.

By the application of the signal throughout a filter-bank, represented by h_0 and h_1, are obtained the coefficients $a_{j,k}$ and $b_{j,k}$, that represent the approximation and detail coefficients of the original signal at a level j [3], respectively. The signals at the output of the high-pass filters will the called detail signals in the context of the present work.

C. Choosing the Wavelet Transform

As mentioned before, differently from FT, WT has several possible bases, resulting from several mother wavelets. Thus, it is necessary to choose the most appropriated one to the analysis of a particular signal. The "best" base would be the one that was able to represent the original signal with a smaller number of significant coefficients $a_{j,k}$ and $b_{j,k}$. Based on this principle, the criterion to determinate the most suitable mother wavelet to analyze PCG signals is based on the comparison among normalized energies of the detail coefficients that were obtained from the set of classical wavelets. The most suitable wavelet would be the one that presents the greater energy concentration in the smaller number of coefficients, indicating its characteristic of representing the signal with optimized coefficients. The procedure also indicates which detail levels, $b_{j,k}$., are the most significant for each tested wavelet. In the comparison procedure, the energy of the detail coefficients was normalized by the signal energy in order to better compare the various candidate wavelets.

D. Detection of S1 and S2 Based on Detail Signals

Since the most suitable wavelet and its most significant detail levels, $b_{j,k}$, have been selected, an heuristic technique for detection of the constituents of the PCG signal, S1 and S2, was designed. The technique is based on the energy of the most significant detail signals and in the presumption that the detection of S2 can only occur, at least, 140ms after the detection of S1. The block diagram of Fig. 2 describes the complete detection method.

One can see in Fig.2 that the signal detection to the S1 event, *det1*, is generated by the comparison between the compounded energy signal d*et1'*. The later signal is obtained multiplying the energy signals e4, e5 and e6 (energy signals derived from the detail signals b4, b5 and b6, respectively) and a fraction (determined by the constant k_1) of the adaptive level obtained from the temporal average of the energies e4, e5 and e6.

The signal detection to the S2 event, *det2*, is reached by the information of the compounded energy *det2'*. This signal is obtained from the energy signals e3 and e4; the logical temporal gate of 140ms (which is generated after the trailing edge of *det1*) and a fraction (derived from the constant k_2) of the same adaptive level used in the detection of *det1*.

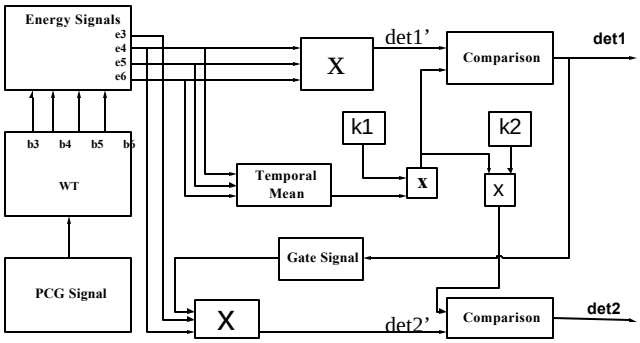

Fig. 2. Block diagram of the proposed method for detection of the S1 and S2 in PCG signals.

E. Materials

Nineteen volunteers (10 normal and 9 abnormal) participated in the data acquisition, that was performed in the Hypertension Division of the National Institute of Cardiology Laranjeiras, Rio de Janeiro, Brazil. The PCG signals have been acquired with a piezoelectric contact transducer (HP 21050 A/B) with flat frequency response in the range of 0.2-2000Hz. Although the proposed methodology does not use the ECG signal, this signal was also acquired in all volunteers in order to supply a reference signal to test the new technique. It is known that S1 must occur after the QRS complex and that S2 must follows the T-wave of the ECG signal [5].

The signals have been recorded in a PC microcomputer (Pentium 200MHz) equipped with a National Instruments DAQ board (AT-MIO-16) 12 bit accuracy and sampling frequency of 2000Hz. A specific electronic circuit was designed to signal conditioning before its acquisition by the DAQ board.

A cardiologist of the hospital that also placed the PCG transducer and ECG electrodes has determined the PCG acquisition sites. The 9 abnormal volunteers presented different types of heart diseases, being the principals: aortic insufficiency (AI), aortic stenoses (AS) and mitral insufficiency (MI). From the 19 volunteers, 756 cycles were used to evaluate the performance of the proposed method.

III. RESULTS

The classical wavelets tested as candidates to the most suitable wavelet to analyze the PCG signals were the *Daubechies* (4 to 19), *Meyer* and *Morlet*. Part of the obtained results in this searching process is represented in the Table I. In this case, the analyzed PCG signal was a normal one. It can be observed that the *Daubechies*-5 presents the best concentration of energy in the detail coefficients b3, b4, b5 and b6. It can be also seen that among all the coefficients $b_{j,k}$, b4 shows the highest energetic value, representing about 81% of the total energy of the analyzed PCG signal. Thus, considering the adopted criterion, the *Daubechies*-5 wavelet was select as the most suitable to the analysis of the acquired PCG signals.

TABLE I

NORMALIZED ENERGY OF COEFFICIENTS b0 TO b9 FOR SOME *DAUBECHIES WAVELET* TESTED AS CANDIDATES TO THE MOST SUITABLE *WAVELET*. THE MNEMONIC Db*i* STANDS *i-th* CLASS OF *DAUBECHIE'S* WAVELET AND b*j* ITS *j-th* DETAIL COEFFICIENTS.

	Daubechie's Wavelets				
b*j*	**Db4**	**Db5**	**Db7**	**Db8**	**Db9**
b9	0.0000	0.0000	0.0000	0.0000	0.0000
b8	0.0001	0.0001	0.0001	0.0001	0.0001
b7	0.0016	0.0014	0.0010	0.0009	0.0009
b6	**0.0279**	**0.0334**	**0.0171**	**0.0282**	**0.0278**
b5	**0.5074**	**0.0759**	**0.5880**	**0.2030**	**0.1264**
b4	**0.3620**	**0.8064**	**0.2630**	**0.6692**	**0.7449**
b3	**0.0789**	**0.0760**	**0.1172**	**0.0824**	**0.0939**
b2	**0.0207**	0.0066	**0.0132**	**0.0158**	0.0059
b1	0.0013	0.0001	0.0004	0.0004	0.0001
b0	0.0001	0.0000	0.0000	0.0000	0.0000
	Db10	**Db11**	**Db13**	**Db14**	**Db18**
b9	0.0000	0.0000	0.0000	0.0000	0.0000
b8	0.0001	0.0001	0.0001	0.0001	0.0000
b7	0.0009	0.0008	0.0007	0.0008	0.0008
b6	**0.0130**	**0.0284**	**0.0118**	**0.0288**	**0.0212**
b5	**0.5284**	**0.3988**	**0.3423**	**0.5214**	**0.3877**
b4	**0.3350**	**0.4518**	**0.5387**	**0.3301**	**0.4731**
b3	**0.1194**	**0.1083**	**0.0999**	**0.1147**	**0.1125**
b2	0.0032	**0.0117**	0.0064	0.0040	0.0046
b1	0.0000	0.0002	0.0002	0.0000	0.0000
b0	0.0000	0.0000	0.0000	0.0000	0.0000

Fig. 3 shows an example of the method described by the block diagram of Fig. 2 for a normal PCG signal, when the *Daubechies*-5 is applied. It can be observed that the method detects correctly the constituents S1 and S2 of the cardiac sounds, that can be confirmed by the ECG signal, used only as a repair signal.

Fig. 4 illustrates an example obtained from a PCG signal in the presence of systolic murmur (Aortic Stenoses (AS)). It can be seen that even in a murmured pathological signal the proposed method detects correctly the constituents of the cardiac sounds.

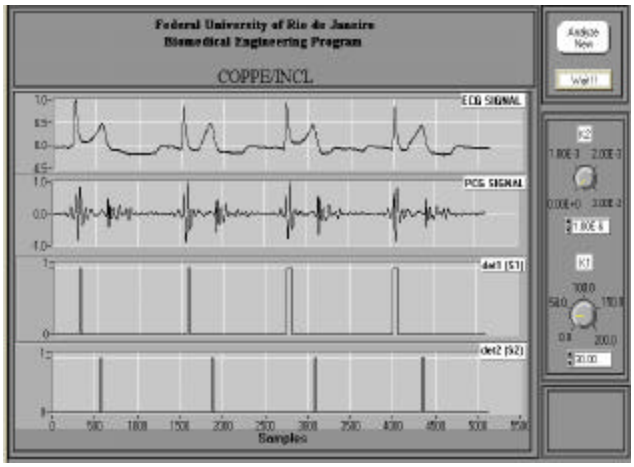

Fig. 3. Detection of the constituents S1 and S2 of a normal PCG signal k_1=30 and k_2 =10^{-6}.

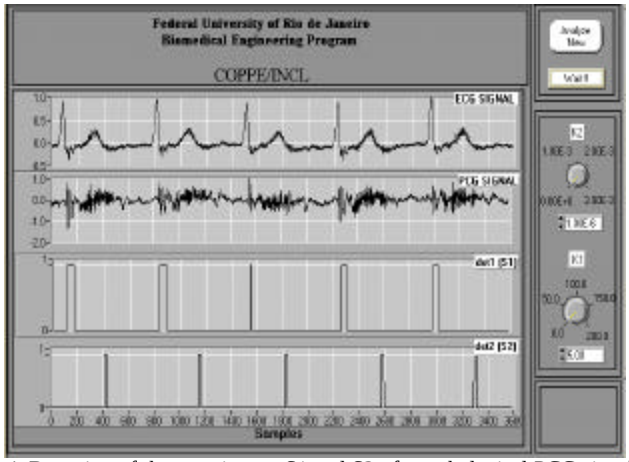

Fig. 4. Detection of the constituents S1 and S2 of a pathological PCG signal (Aortic Stenoses (AS)). k_1=5 and k_2 =10^{-6}.

Table II shows the total number of subjects analyzed in this study as well as the right-ratio reached by the proposed method. It can be observed that even in presence of an intense murmur (M) the method reaches 98% correctness in the detection of S1 and S2.

TABLE II

STATISTICAL EVALUATION OF THE METHOD. N(NORMAL); As (AORTIC STENOSES); AI (AORTIC INSUFFICIENCY); M (MORE THAN ONE PATHOLOGY ASSOCIATED)

Number of Subjects	Pathology	Number of cycles	Number of errors	Right-ratio (%)
10	N	347	2	99.42
3	AE	131	1	99.24
3	AI	163	1	99.39
3	M	115	2	98,26
19	Total	756	6	99.20

IV. Discussion and conclusion

The literature shows some works that present methods for detection of the correct timing of the constituents S1 and S2 of the cardiac sounds, based only on the PCG signal. These methods are generally focused on the Fourier Analysis and on the signal envelope of energy. However, these methods do not present good results when applied to pathological PCG signals because the presence of strong systolic murmurs [2].

The present study proposes a new method based on wavelet analysis for correct detection of S1 and S2 even in pathological cases. The method presents 98% (Table II) of correctness in detection of S1and S2, even in cases where a significant amount of murmur exists.

A natural continuity of the present study would be the investigation of the sub-events detection inside each cardiac event S1 and S2, i.e., the timing of their components that are strictly related to the opening/closing of the cardiac valves.

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